Accessible Near-Earth Objects (NEOs)

Presented to the 12th Meeting of the NASA Small Bodies Assessment Group (SBAG)

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Defining NEO Accessibility Factors

- **Astrodynamical**
  - Earth departure dates; mission Δv; mission duration; stay time; etc
- Physical
  - NEO size(?); rotation rate; dust/satellites environment; chemistry; etc
- Architectural
  - Launch vehicle(s); crew vehicle(s); habitat module(s); budget; etc
- Operational
  - Operations experience; abort options/profiles; etc

Astrodynamical Accessibility is the starting point for understanding the options and opportunities available to us.

Here we shall focus on Astrodynamical Accessibility.

Development of accessibility aspects may occur in parallel.

Astrodynamical Accessibility (NHATS)

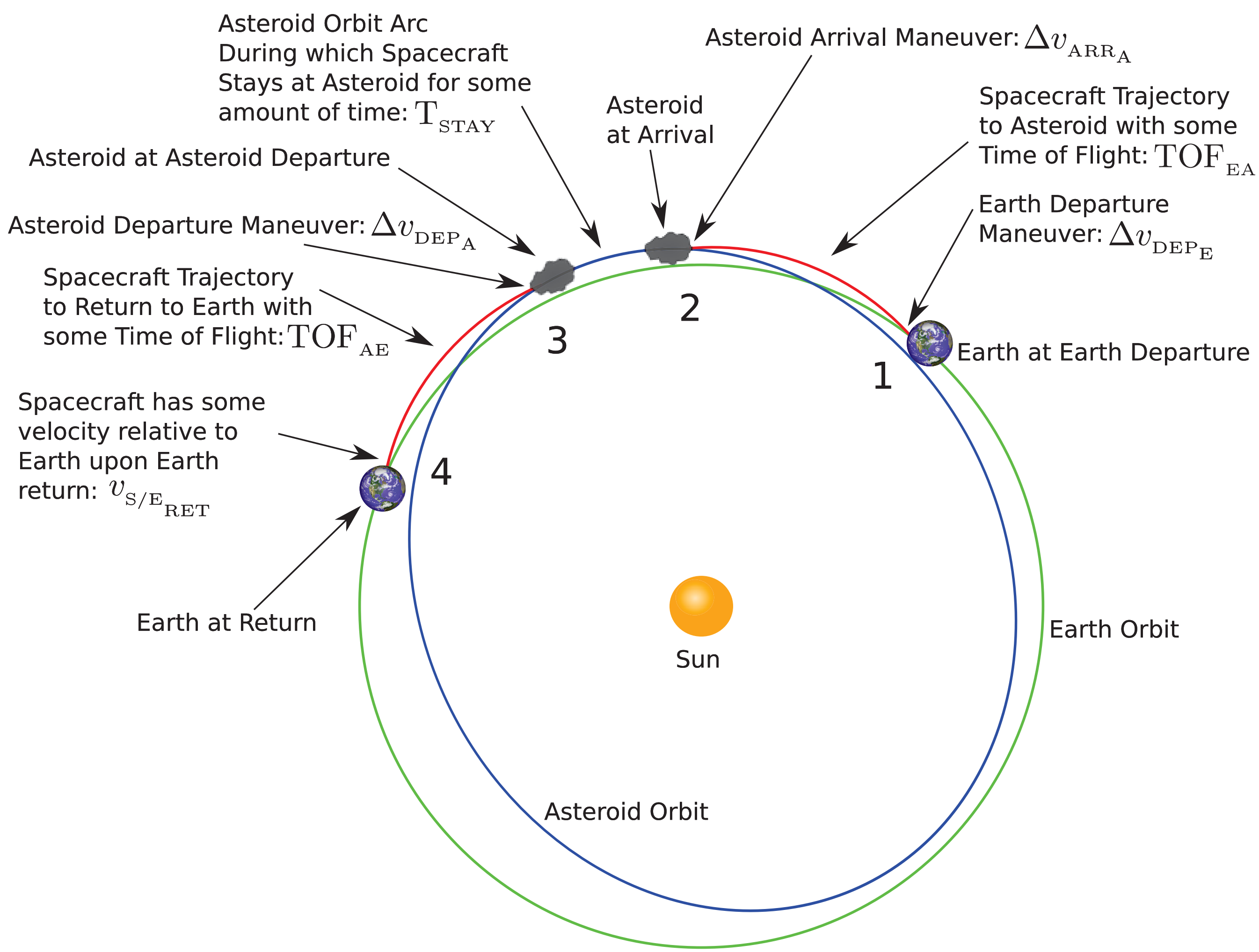
- Earth departure date between 2015-01-01 and 2040-12-31
- Earth departure $C_3 \leq 60$ km^2/s^2
- Total mission $\Delta v \leq 12$ km/s
  - The total Δv includes (1) the Earth departure maneuver from a 400 km altitude circular parking orbit, (2) the maneuver to match the NEA's velocity at arrival, (3) the maneuver to depart the NEA and, (4) if necessary, a maneuver to control the atmospheric re-entry speed during Earth return.
- Total round trip mission duration ≤ 450 days
- Stay time at the NEA ≥ 8 days
- Earth atmospheric entry speed ≤ 12 km/s at an altitude of 125 km

A near-Earth asteroid (NEA) that offers at least one trajectory solution meeting those criteria is classified as NHATS-compliant.

http://neo.jpl.nasa.gov/nhats/

Profile of a Human Mission to an NEA

The purpose of NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) (pron.: /næts/) is to identify known near-Earth objects (NEOs), particularly near-Earth asteroids (NEAs), that may be accessible for future human space flight missions. The NHATS also identifies low Δv robotic mission opportunities.



Putting Accessibility Into Context

- What does "accessible NEO" mean? "Accessible" compared to what?
- Other solar system destinations:

Destination	**Total Δv (km/s)**	**Round-Trip Mission Duration (days)**
Lunar orbit	$\sim$5	$\sim$One to several weeks
Lunar surface	$\sim$9	$\sim$One to several weeks
Mars Surface	12.53	923 *(500 day stay)*
Elliptical Mars Orbit	6.29	923 *(500 day stay)*
Elliptical Mars Orbit	12.14	422 *(7 day stay)*
Elliptical Mars Orbit (w/ Venus flyby)	12.81	485 *(45 day stay)*
Elliptical Mars Orbit (w/ Venus flyby)	8.12	588 *(45 day stay)*
Mars flyby	9.01	501 *(0 day stay)*
Mars flyby (w/ Venus flyby)	6.07	582 *(0 day stay)*
Phobos/Deimos	*Similar requirements to Mars*	

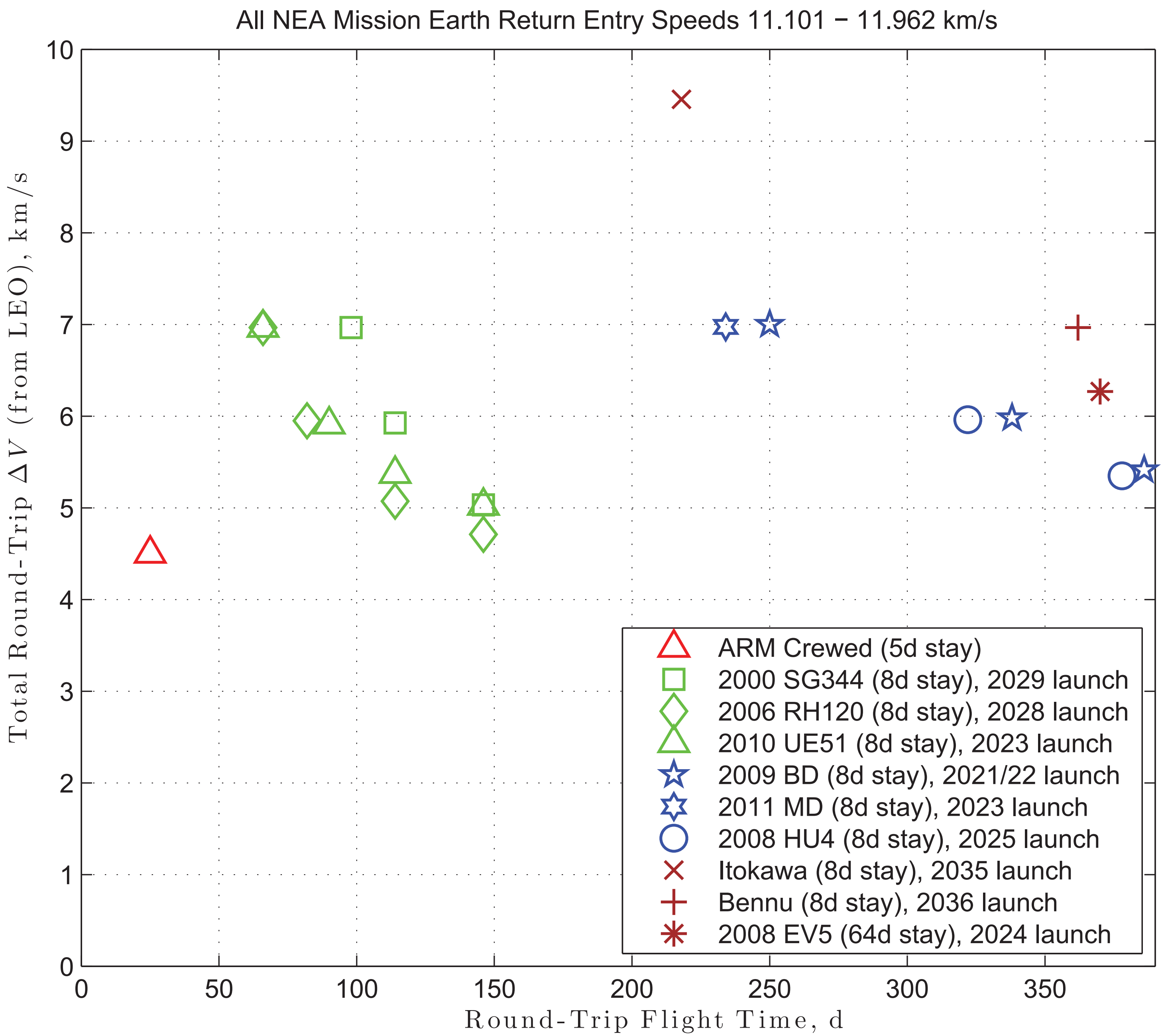
- Many Mars/Phobos/Deimos mission trajectories pass within Venus distance ($\sim$0.7 AU) of the Sun, or closer (thermal/radiation issues)

No round-trip mission to Mars (orbit, surface, or flyby) or Phobos/Deimos is possible with both $\Delta v \leq$12 km/s AND mission duration $\leq$450 days.

Putting Accessibility Into Context

- As of 2014-12-06, **1317** NHATS-compliant NEAs have been discovered
- Of those,
  - **49** can be visited and returned from for less Δv than **Lunar orbit**
  - **556** can be visited and returned from for less Δv than **the lunar surface**
  - All **1317** are more accessible than **Mars, Phobos, or Deimos**
- More and more NHATS-compliant NEAs are being discovered and identified
- The NHATS data processing is automated, observers are automatically notified, web-site is updated daily

Comparisons to ARM



Putting it all together ...

(Available Online at: `http://www.lpi.usra.edu/sbag/science/`)

Accessible Near-Earth Asteroids (NEAs)

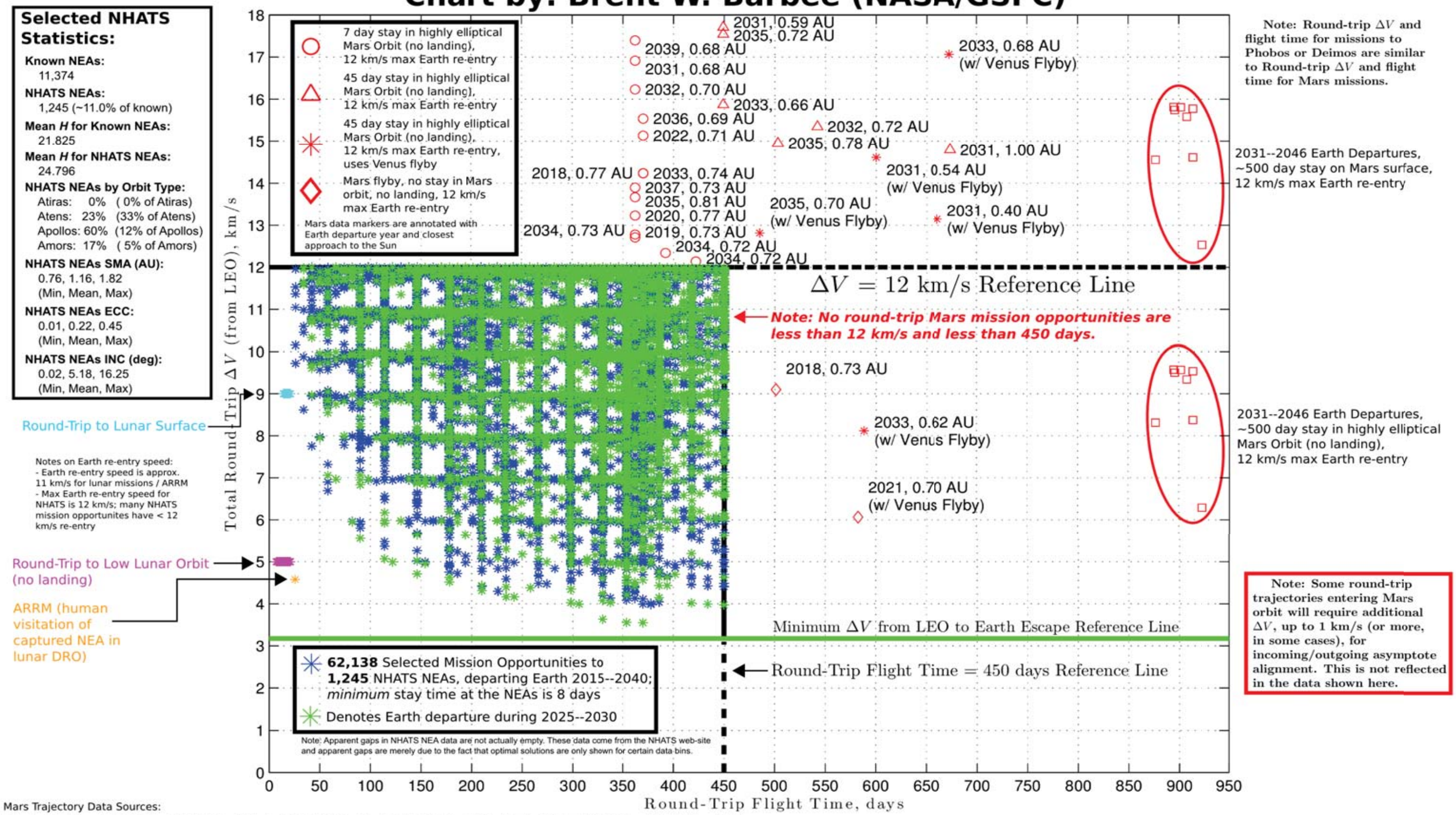
Goals of the Near-Earth Object Human Space Flight Accessible Targets Study (**NHATS**):

- Monitor the accessibility of the NEA population for exploration missions.
- Characterize the population of **accessible NEAs**.
- Rapidly notify observers so that crucial follow-up observations can be obtained.

NHATS data shown here current as of: 2014-09-14

NHATS Web-site: `http://neo.jpl.nasa.gov/nhats/` **NHATS Daily Updates:** `https://lists.nasa.gov/mailman/listinfo/nhats`

Chart by: Brent W. Barbee (NASA/GSFC)



Mars Trajectory Data Sources:

7 day stay Mars data: Folta, D., Barbee, B. W., Englander, J., Vaughn, F., Lin, T. Y., "Optimal Round-Trip Trajectories for Short Duration Mars Missions," AAS/AIAA Paper AAS 13-808, August 2013

45 day stay Mars data: Folta, D., Barbee, B. W., Vaughn, F., "Analysis of Short Duration Round-Trip Mars Mission Opportunities During the Mid-2030s," Internal NASA/GSFC presentation, November 2011

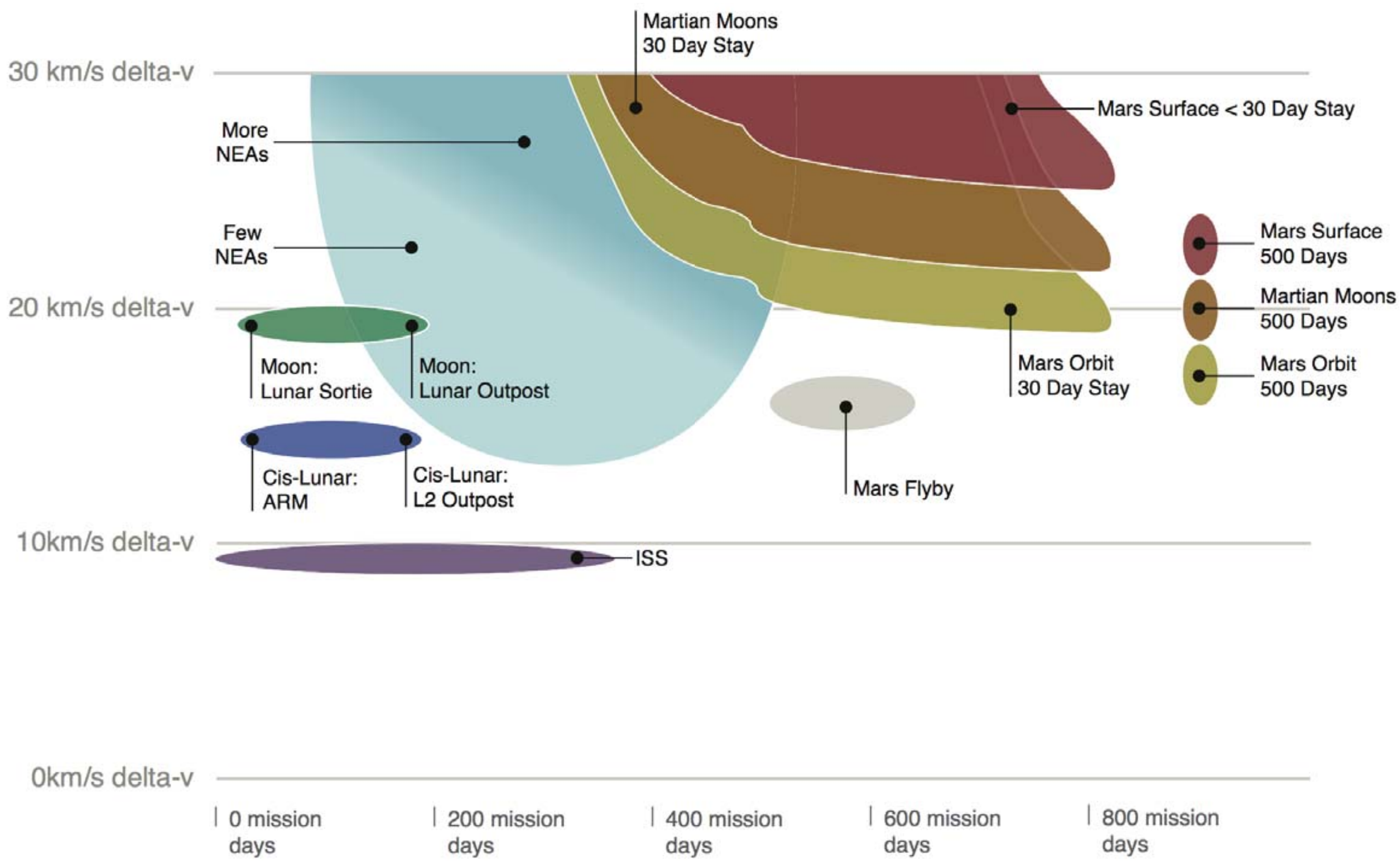
500 day stay Mars data*: Drake, B. G., ed. "Human Exploration of Mars Design Reference Architecture 5.0 Addendum," NASA/SP-2009-566-ADD, July 2009, http://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf *(w/ adjustments by B. W. Barbee for 12 km/s max Earth re-entry)

Mars flyby data: Adamo, D. R. analysis of http://inspirationmars.org/Written_Testimony_DTito_Nov2013.pdf and http://www.youtube.com/watch?v=pdu7Kk5si1k", with input from Loucks, M.

Communicating all of this to the public, and even to technical folks who are non-specialists, is very challenging.

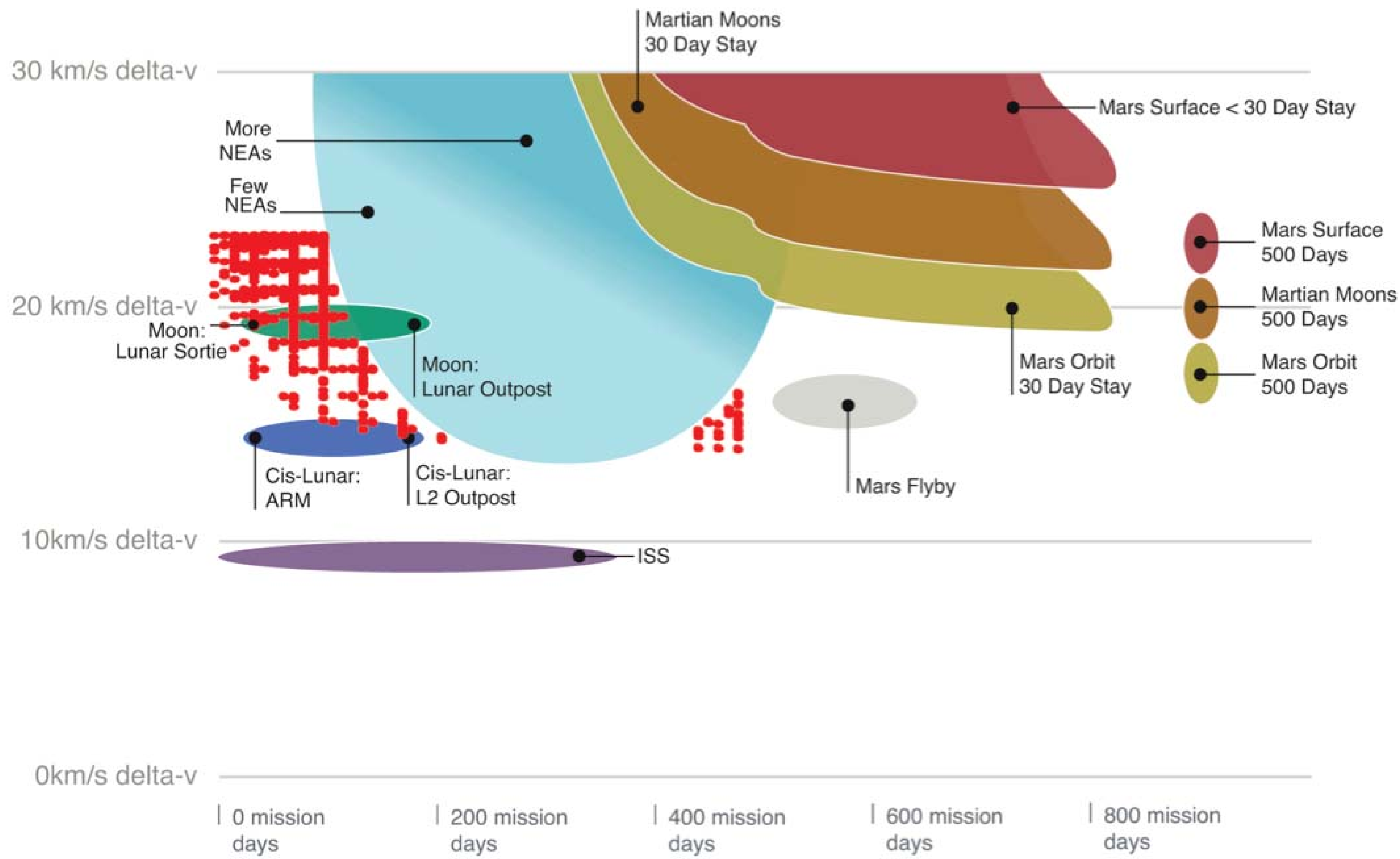
NRC's "Pathways to Exploration" Report (draft)

BEFORE Dr. Richard Binzel's 8 July 2014 Letter
to the NRC and NAC pointing out the existence of NHATS data ...



Adding The Missing NHATS Data

The missing NHATS data overlaid on the original NRC figure, from Dr. Richard Binzel's 8 July 2014 Letter to the NRC and NAC



NRC's "Pathways to Exploration" Report (final)

AFTER Dr. Richard Binzel's 8 July 2014 Letter to the NRC and NAC

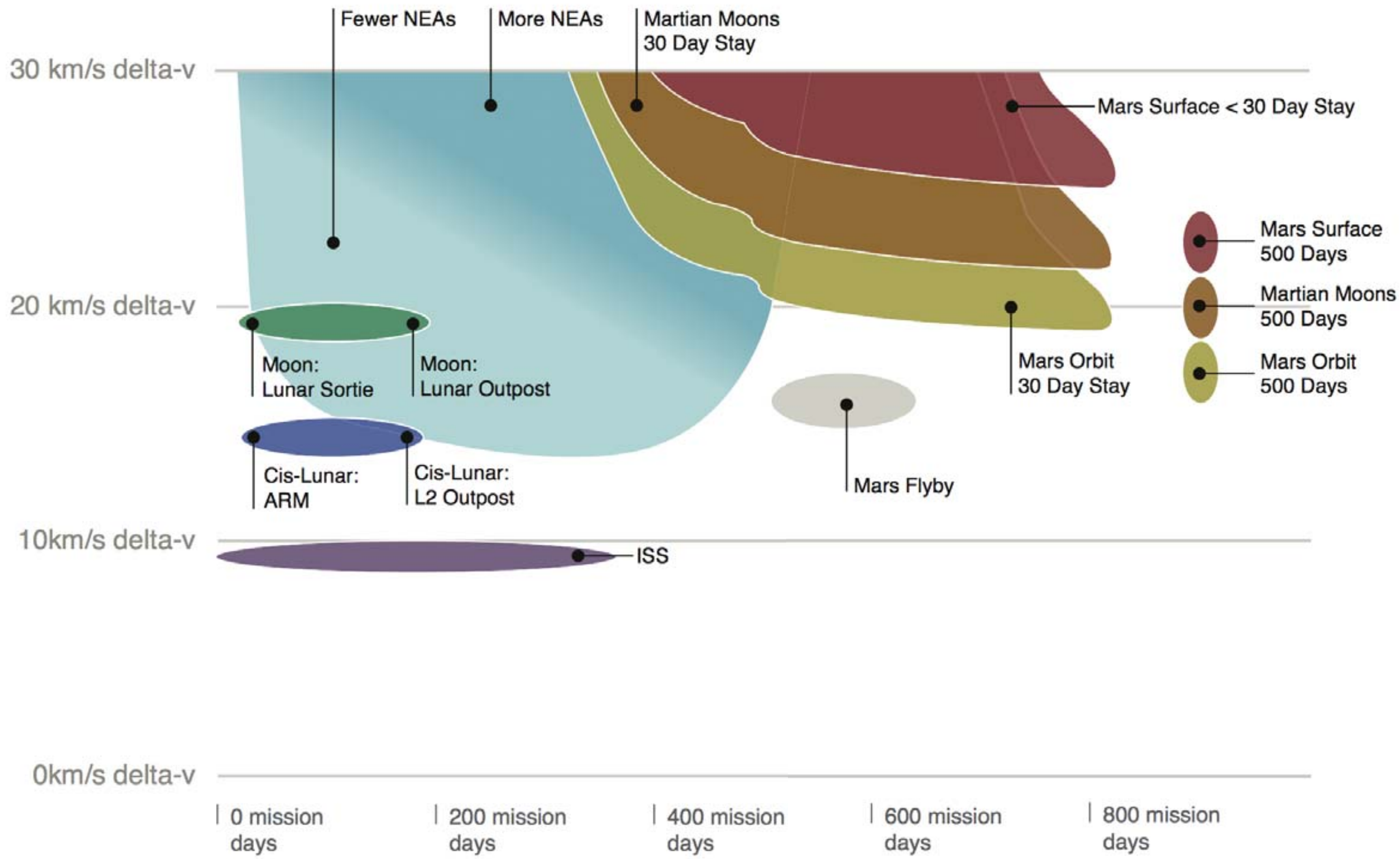
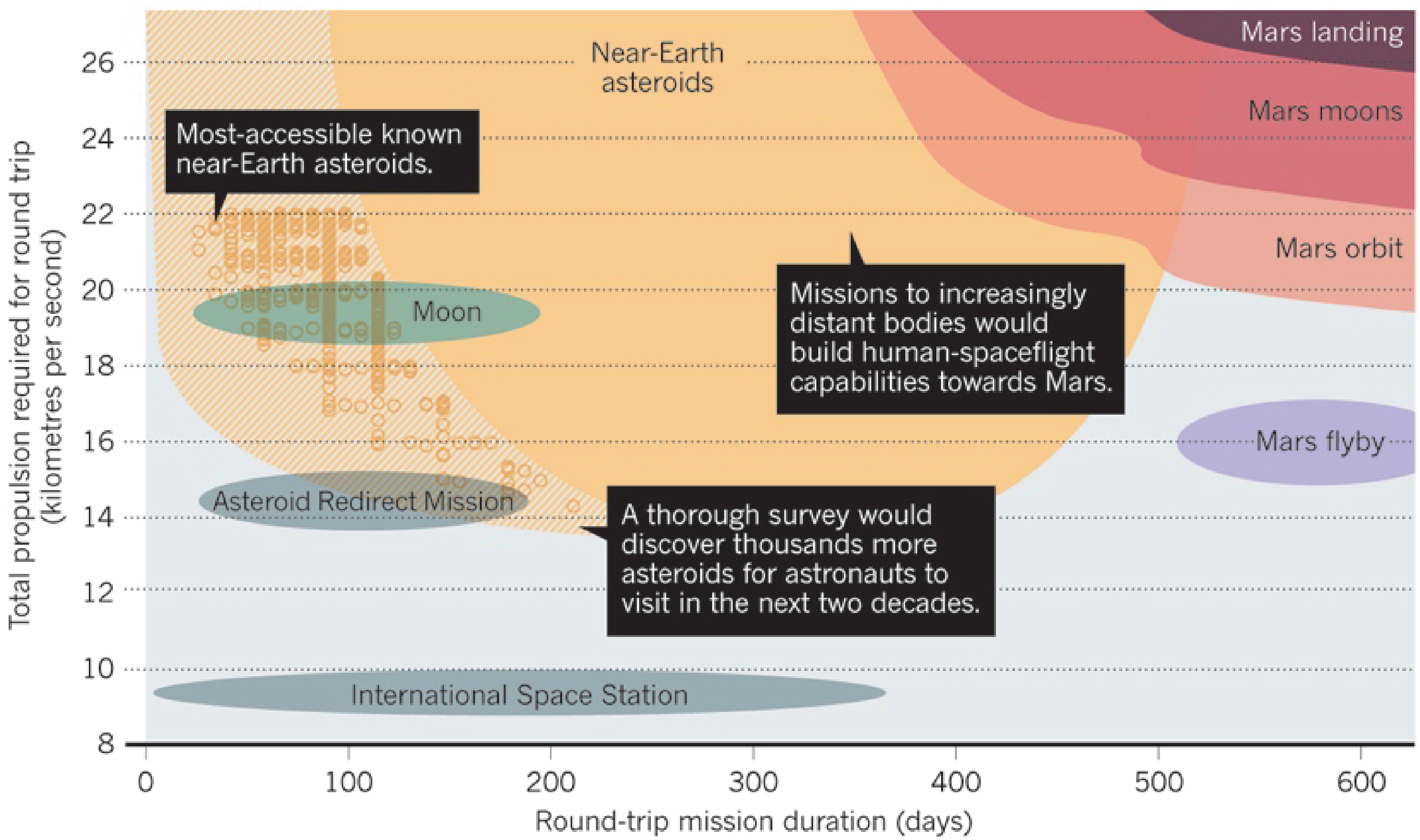


Figure 1.9 in:
http://www.nap.edu/catalog/18801/pathways-to-exploration-rationales-and-approaches-for-a-us-program

Recent *Nature* Article

MISSION REQUIREMENTS

A mission to a near-Earth asteroid would require less propulsion and a shorter mission duration than a human mission to Mars. Less than 1% of the most-accessible asteroids are currently known (yellow circles), but a dedicated survey (filling in the yellow-hatched region) would reveal abundant asteroid stepping-stone opportunities as a gateway for human interplanetary exploration.



Binzel, R., "Find asteroids to get to Mars," *Nature*, Volume 514, 30 October 2014, pages 559–561
http://www.nature.com/news/human-spaceflight-find-asteroids-to-get-to-mars-1.16216?WT.ec_id=NATURE-20141030
PDF: http://www.nature.com/polopoly_fs/1.16216!/menu/main/topColumns/topLeftColumn/pdf/514559a.pdf

NAC Findings/Recommendations

Excerpt from page 4 of the 4 August 2014 letter to the NASA Administrator from the NASA Advisory Council (NAC); note that (1) the date is *after* Dr. Richard Binzel's 8 July 2014 Letter to the NRC and NAC, and (2) the NAC letter uses the same references as the 8 July 2014 letter

Major Reasons for Proposing the Recommendation: NASA's current Asteroid Initiative has three elements: (1) the search for and identification of Near Earth Asteroid (NEA) targets; (2) redirection of one NEA target to near-lunar orbit; (3) astronaut crew to cis-lunar space to rendezvous with the target and conduct operations. The cost of the second element (asteroid redirect, e.g., ARM) is poorly defined at present. The other elements of the Asteroid Initiative (target search and flights to cis-lunar space) still have merit even if the redirect mission does not take place. It must also be noted that ARM is not a substitute for a mission to an asteroid in its native orbit, which appears to be possible at a lower launch energy than previously believed based on recent data[2-4]. Such a long duration deep space mission would be a logical step toward the horizon goal of humans to Mars. We have concerns that the ARM mission as currently defined may pose an unacceptable cost and technical risk. A prudent response to such concerns is to conduct and independent cost and technical assessment prior to selection.

[2]*NHATS: Near-Earth Object Human Space Flight Accessible Targets Study.* http://neo.jpl.nasa.gov/nhats/

[3]*Barbee, B. (2014). NASA Small Bodies Assessment Group (SBAG) Science Nuggets.* http://www.lpi.usra.edu/sbag/science/NHATS_Accessible_NEAs_Summary.png

[4]*Barbee, B., Abell, P.A., Adamoc, D.A., Alberdinga, C.M., Mazanek, D.D., Johnson, L.N., Yeomans, D.Y., Chodas, P.W., Chamberlin, A.B., Friedenseng, V.P. (2013). "The Near-Earth Object Human Space Flight Accessible Targets Study: An Ongoing Effort to Identify Near-Earth Asteroid Destinations for Human Explorers." Planetary Defense Conference 2013 IAA-PDC13-04-13.*

(http://www.nasa.gov/offices/nac/meetings/JULY-30-31-2014_presentations.html)
(http://www.nasa.gov/sites/default/files/files/SquyresLetterToBolden_tagged.pdf)
(http://www.nasa.gov/sites/default/files/files/SquyresLetterToBolden.pdf)

How Accessible Can NEOs Be?

- How many accessible NEOs are out there waiting for us to find them?
- And, how accessible are they?
- In future studies we may apply the NHATS algorithms to simulated NEOs predicted by modern NEO population models
- That will at least tell us what additional accessible NEOs are predicted by our population models
- But we won't really know until we deploy a space-based NEO survey telescope
- In the meantime, we can look at some historical NEO accessibility data to gain a sense of just how accessible NEOs in their natural orbits can be

Analysis of 2006 RH_{120} and 2009 BD

- The NHATS system monitors NEA accessibility for missions departing Earth 2015–2040
- However, some NEAs offered their best mission opportunities during time frame surrounding when they were discovered
- To illustrate this, during July of 2014 Paul Chodas and I investigated the mission accesibility of two NEAs: 2006 RH_{120} ($\sim$2–3 m in size) and 2009 BD ($\sim$4 m in size)
  - 2006 RH_{120} was temporarily captured by the Earth from about September 2006 to June 2007
    - But was not given a minor planet designation until February 18, 2008
  - We believe objects the size of 2006 RH_{120} are captured by the Earth about once per decade

Mission Trajectories Comparison

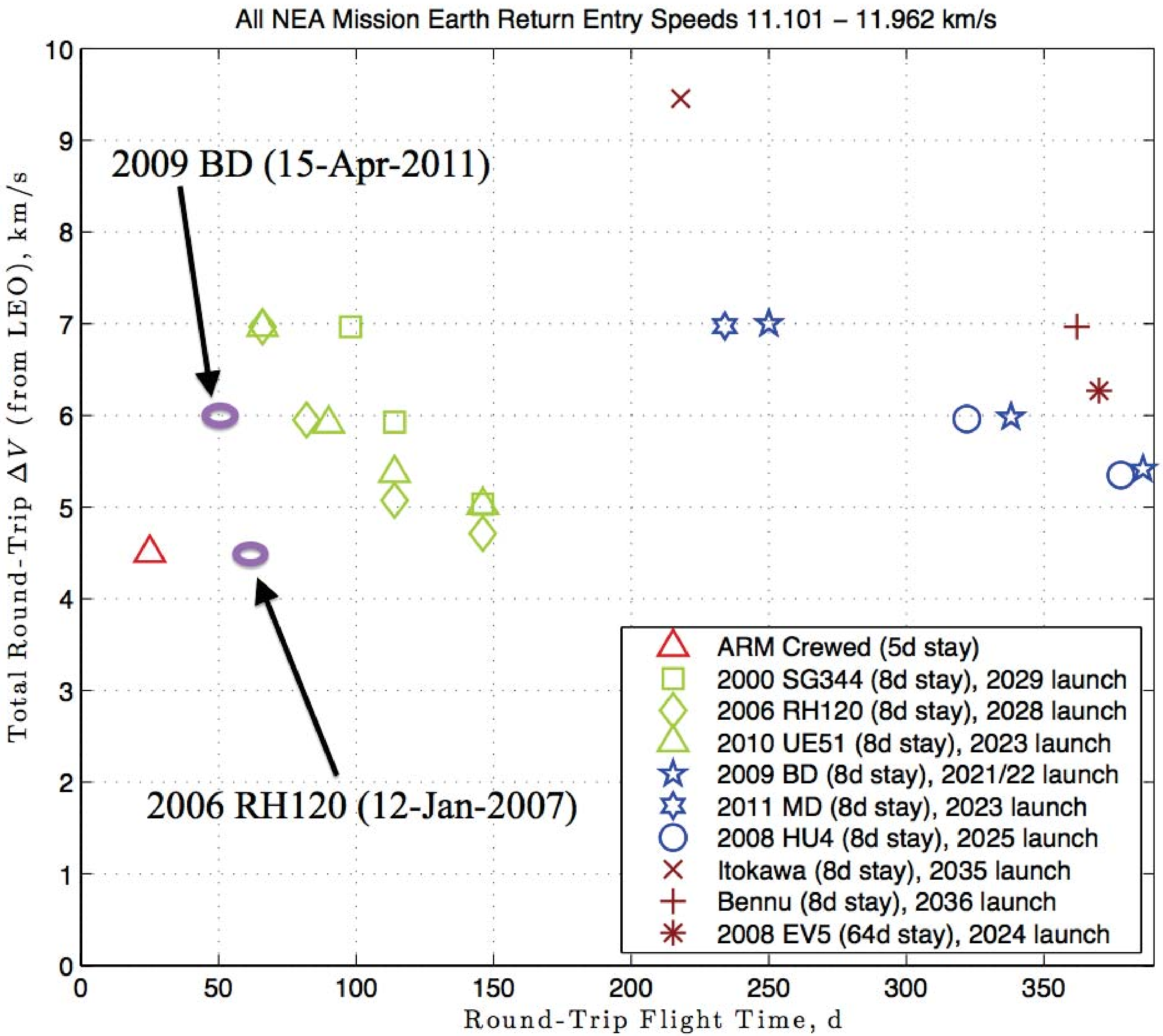
2006 RH_{120}

	$\Delta v \leq 12$ km/s, Dur ≤ 450 d				$\Delta v \leq 4.5$ km/s, Dur ≤ 150 d			
	2015–2040		2006–2007		2015–2040		2006–2007	
	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.
Total Δv (km/s)	3.972	11.942	3.501	9.147	4.711	4.993	3.843	**4.451**
Total Duration (days)	450	34	386	18	146	122	146	**58**
Earth Dep Date	18-Aug-2027	4-Aug-2028	18-Jun-2006	9-Mar-2007	3-Jul-2028	3-Jul-2028	1-Mar-2007	**12-Jan-2007**
Return Entry Speed (km/s)	11.083	12.000	11.085	11.811	11.101	11.112	11.075	**11.091**

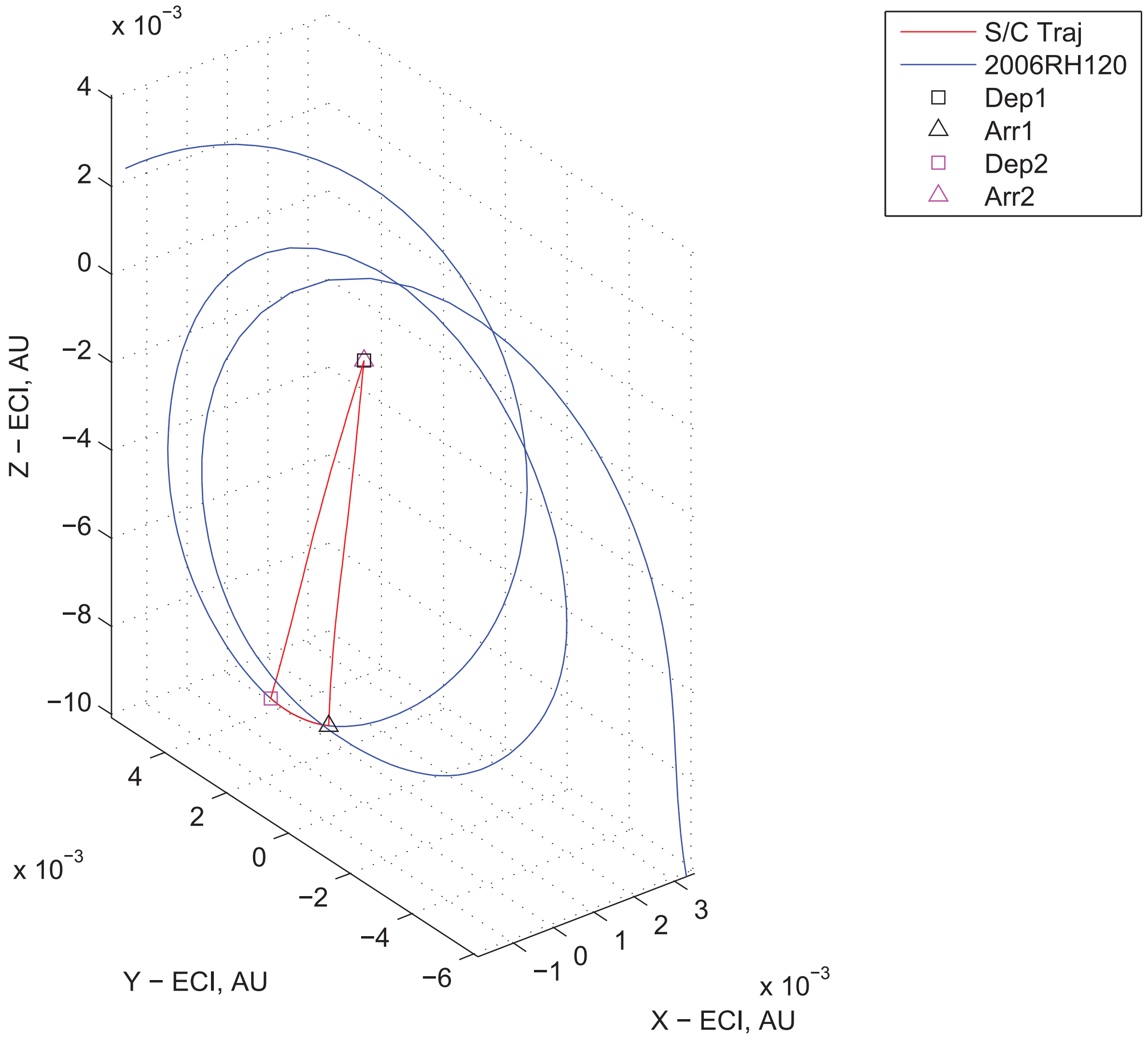
2009 BD

	$\Delta v \leq 12$ km/s, Dur ≤ 450 d				$\Delta v \leq 6.0$ km/s, Dur ≤ 270 d			
	2015–2040		2008–2012		2015–2040		2008–2012	
	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.
Total Δv (km/s)	4.978	11.876	3.464	11.054	5.876	5.964	3.843	**5.998**
Total Duration (days)	370	114	354	18	266	258	258	**50**
Earth Dep Date	30-Nov-2033	25-May-2034	15-Jun-2010	17-May-2011	10-Feb-2034	10-Feb-2034	8-Sep-2009	**15-Apr-2011**
Return Entry Speed (km/s)	11.131	11.909	11.138	11.871	11.181	11.204	11.123	**11.141**

Comparisons to ARM

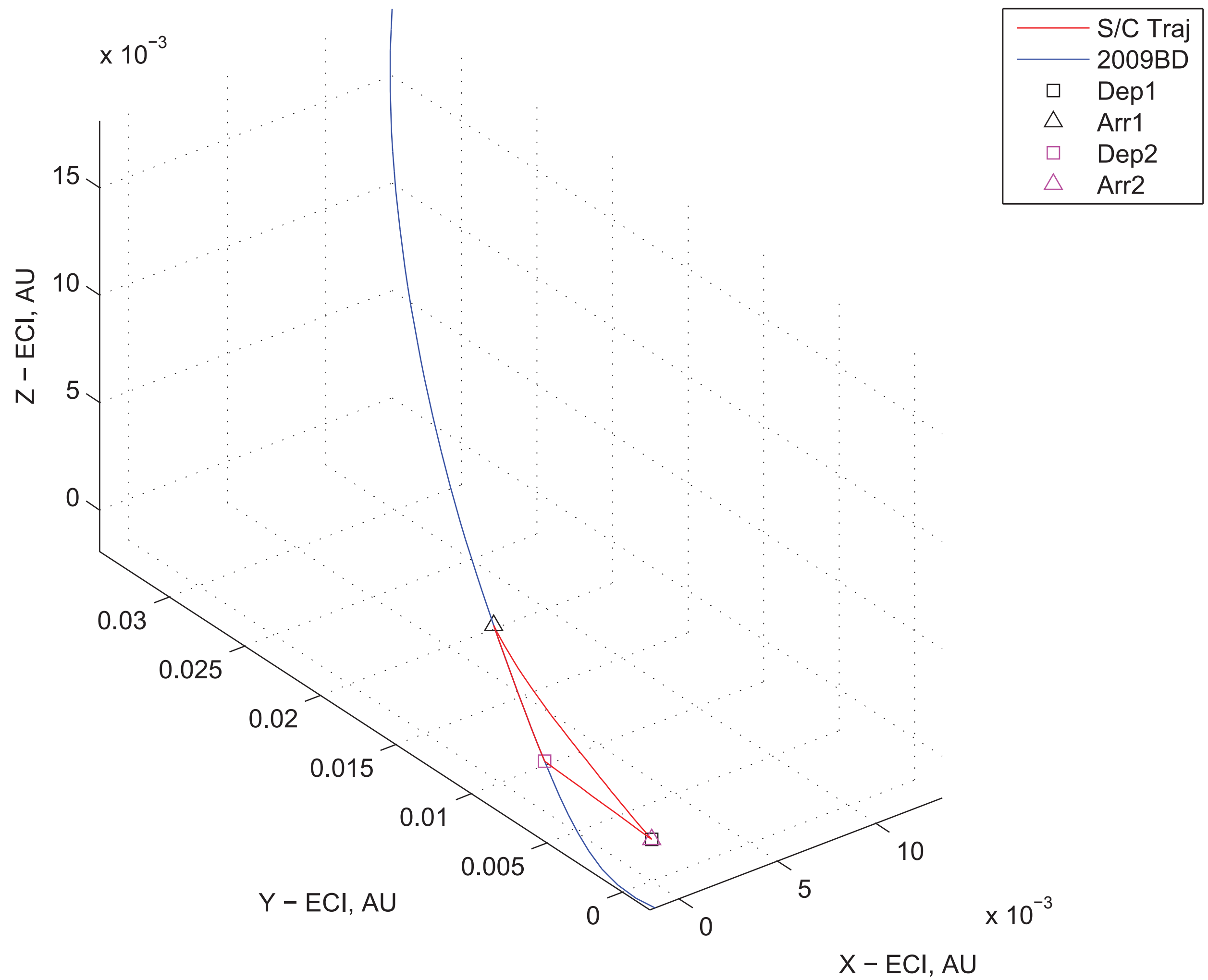


58 Day Mission to 2006 RH_{120}



Earth Departure 2007-01-12

50 Day Mission to 2009 BD

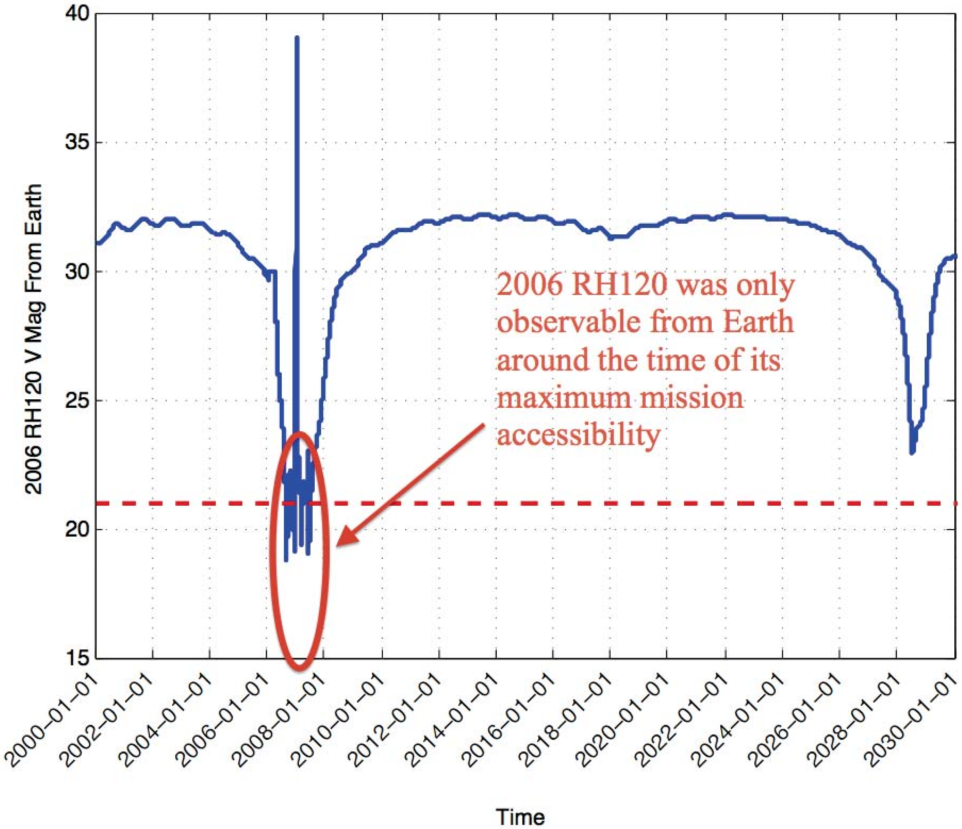


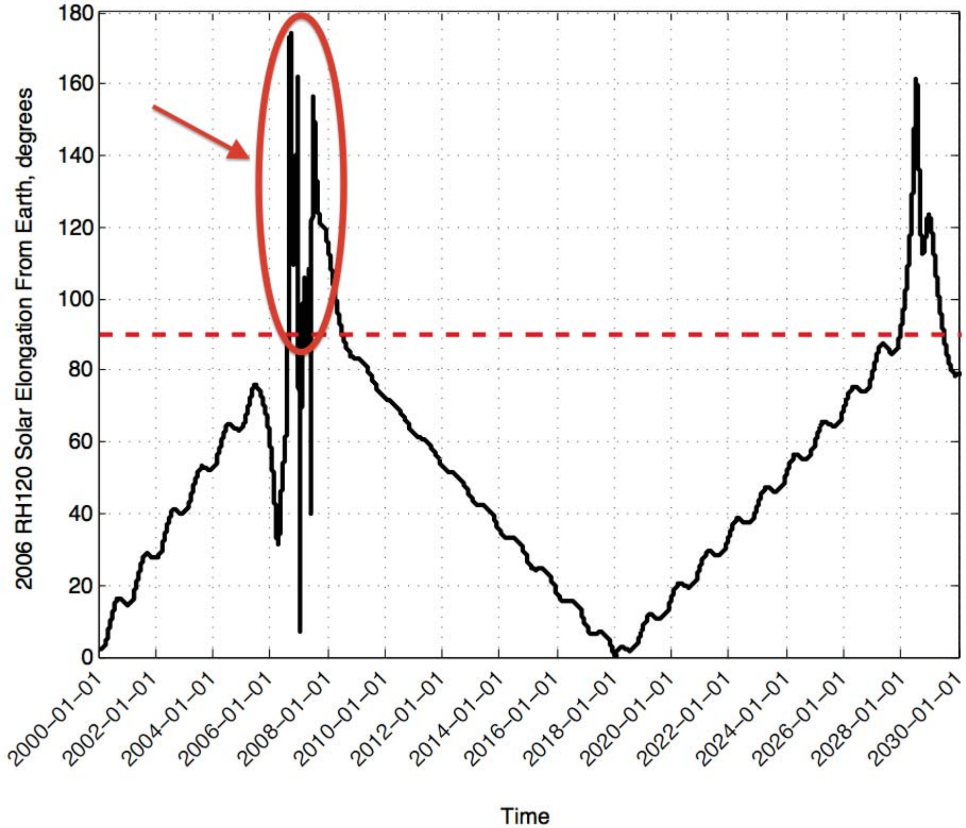
Earth Departure 2011-04-15

Comments on Mission Trajectories

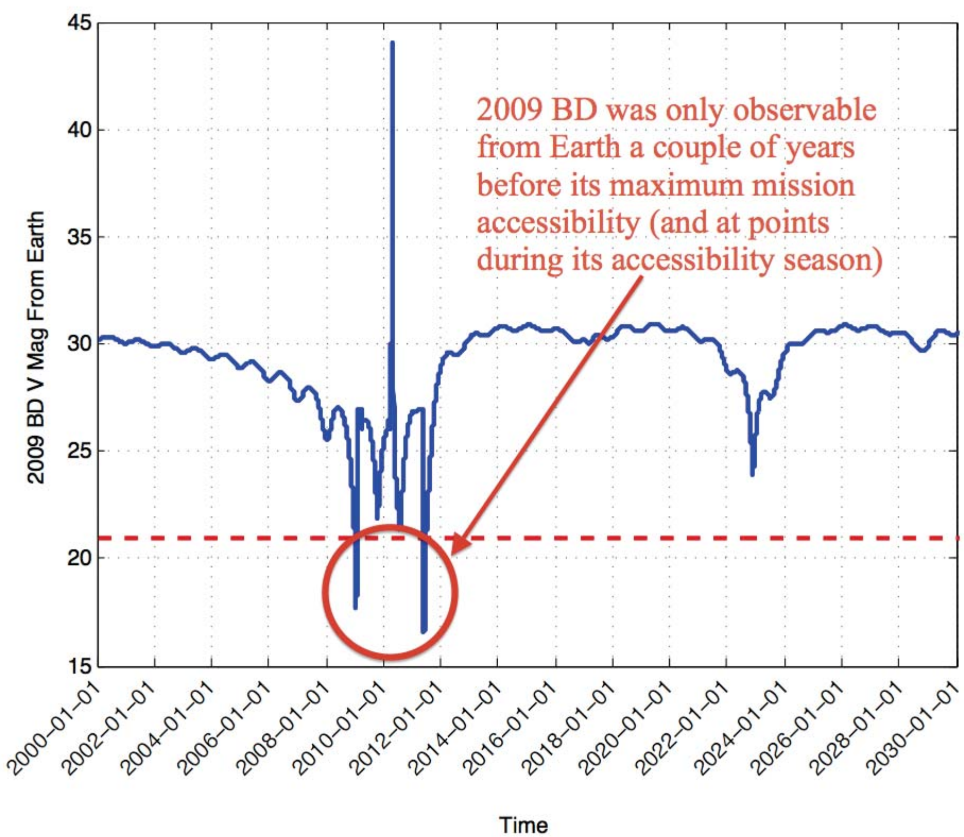
- January 2007 is only a few months after the discovery of 2006 RH_{120}, and a year before the object received its minor planet designation; sufficient time (a long enough arc of observations) is needed to ascertain whether an object is artificial or natural
- Such considerations will generally be important to mission analysis for small NEAs in any context
- On the other hand, April 2011 is a full 2 years after the discovery of 2009 BD and so would likely be a feasible launch date for a mission, at least from the perspective of having a sufficiently long observation arc

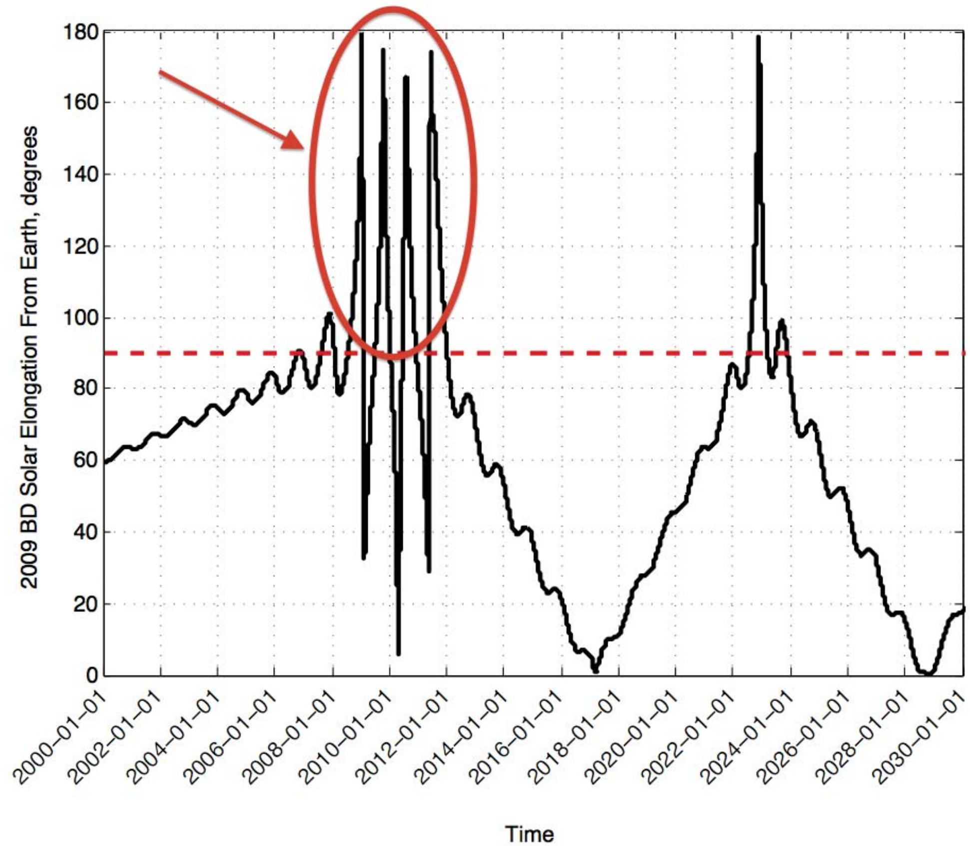
Observability and Accessibility Coinciding





Observability and Accessibility Coinciding





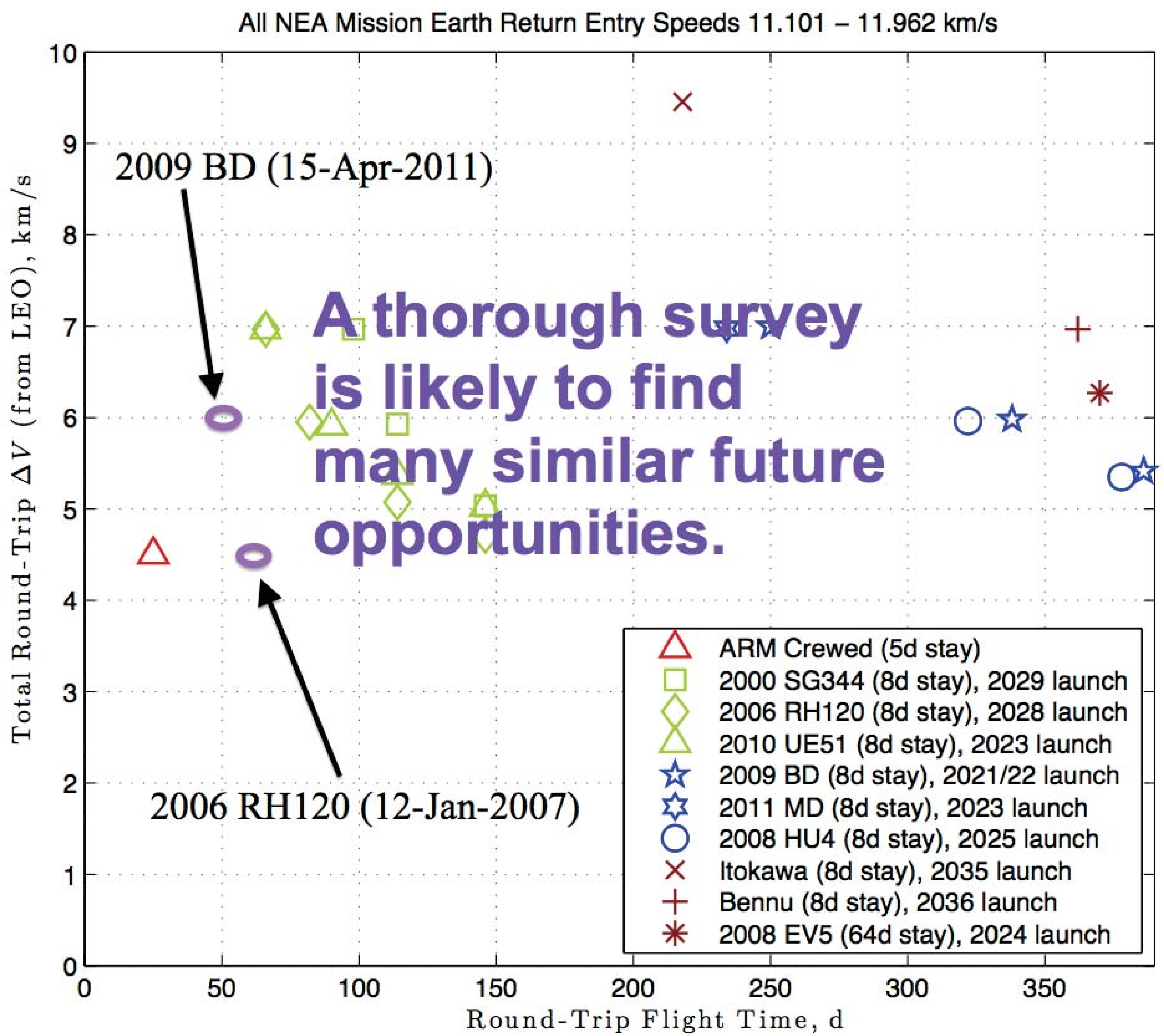
Remarks

- 2006 RH_{120} was most accessible when near Earth, around the time of its discovery
  - When it was a temporarily captured object ("mini-moon"), 2006 RH_{120} offered round-trip mission accessibility approaching that of an object in a lunar DRO
    - Same Δv, but $\sim$2 month round trip rather than $\sim$1 month round trip
  - Subject to the aforementioned caveats and additional considerations
- Though it was not a temporarily captured object, 2009 BD was also most accessible when near Earth, around the time of its discovery
- Both objects offered long accessibility seasons surrounding the times when they were discovered
- Enhanced NEO survey capabilities (e.g., a space-based NEO survey telescope) might have the potential to discover highly accessible NEAs such as these years in advance of their peak mission accessibility seasons, affording us the opportunity to prepare missions to visit them in their native orbits

Conclusions and Findings

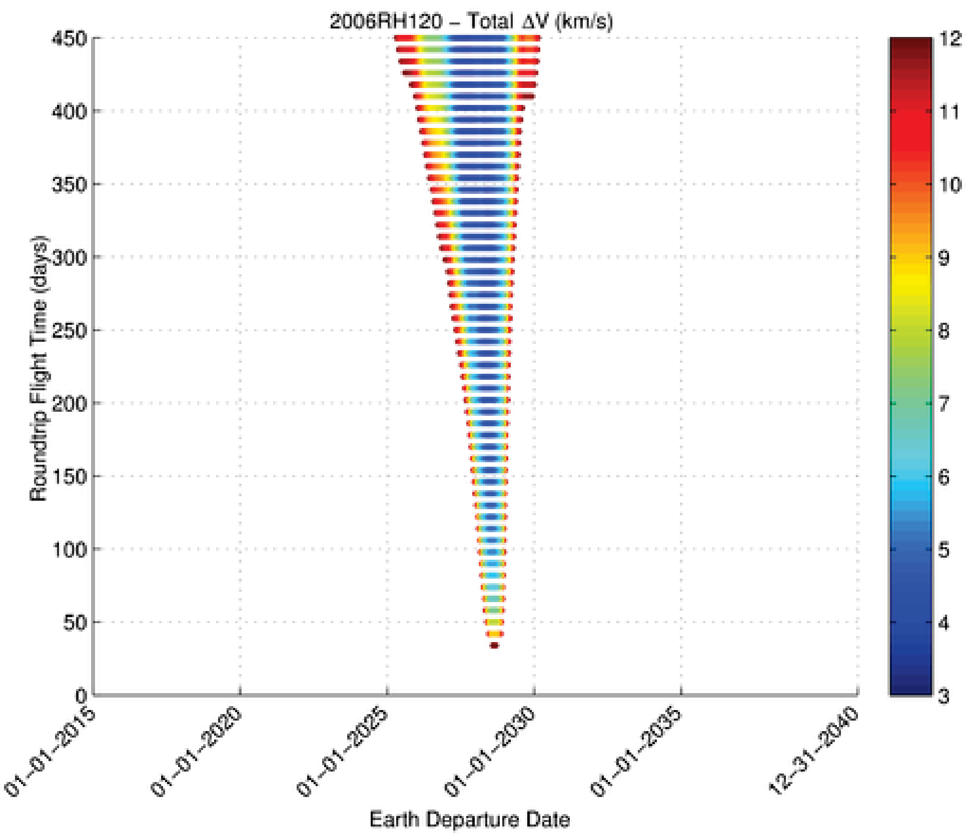
- **Many accessible NEOs have been discovered and identified.**
  - We have an automated system to monitor the accessibility of the NEA population (NHATS).
- **It is likely that many more accessible NEOs are waiting to be found.**
  - Further study is required to learn what modern NEO population models have to say on this point.
- **Findings: Current survey capabilities tend to discover NEOs very close to the times of their optimal mission opportunities.**
  - A space-based NEO survey telescope is needed to discover NEOs with implementable mission opportunities (far enough in advance of their mission opportunities).
  - Such an asset would simultaneously benefit human exploration, planetary defense, and science.

Survey Benefits Human Exploration

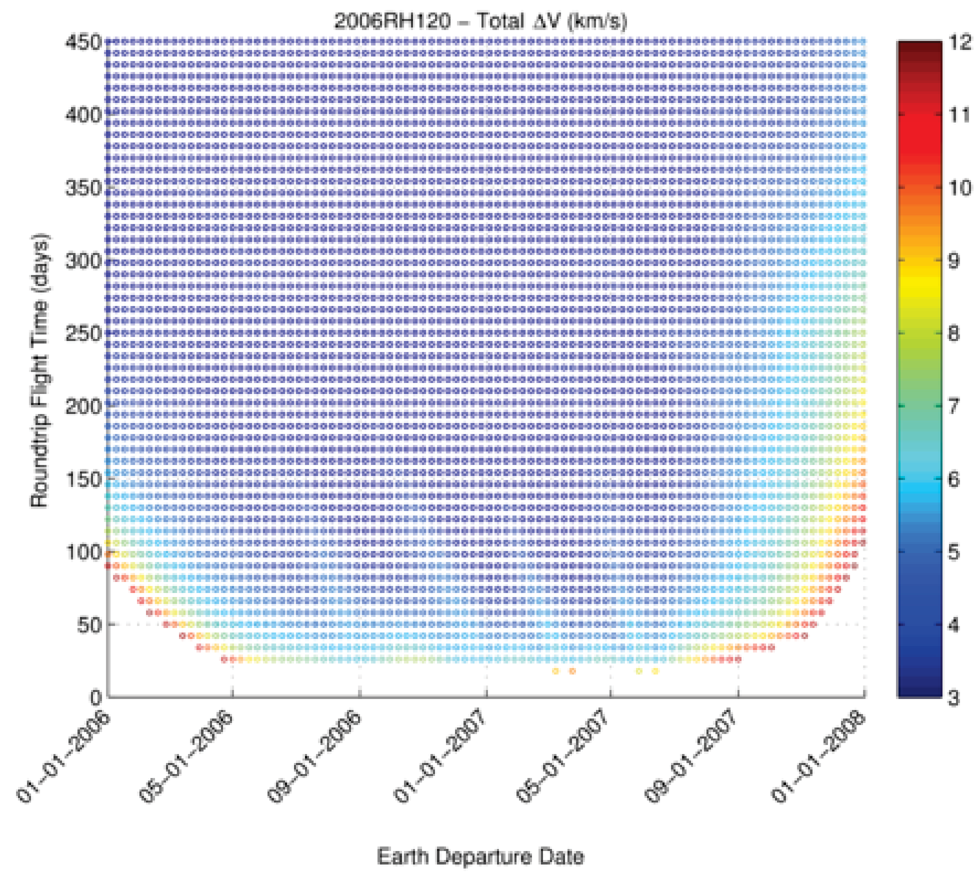


Appendices

PCC Comparison: 2006 RH_{120}

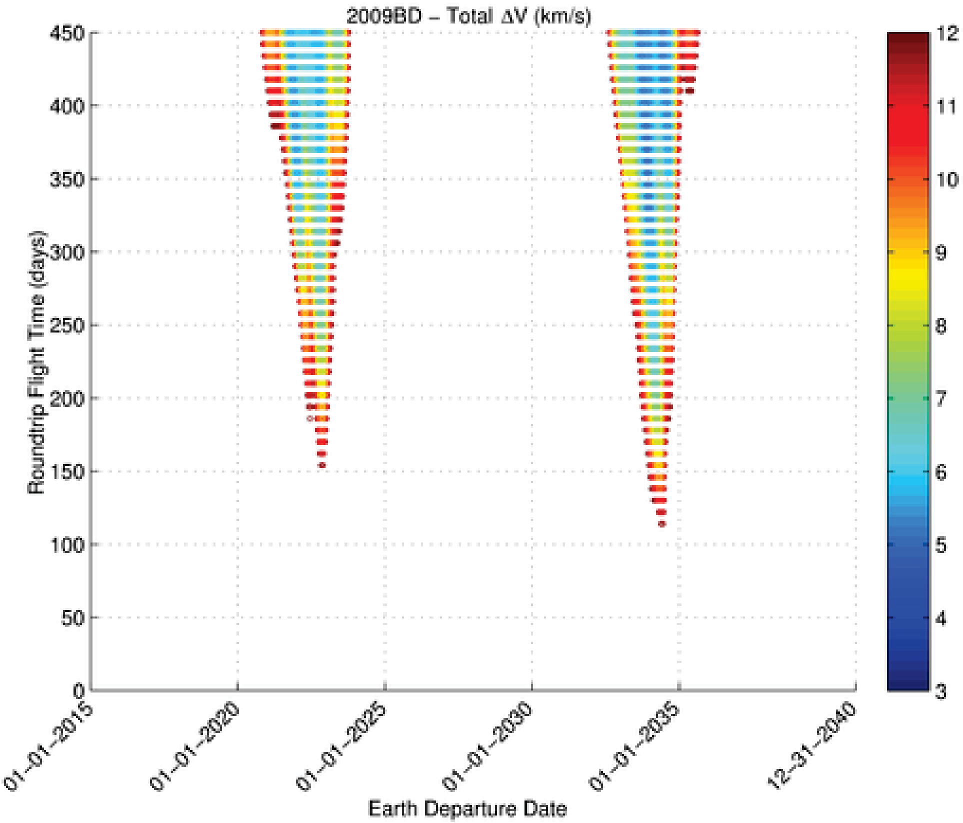


Standard NHATS Analysis 2015–2040

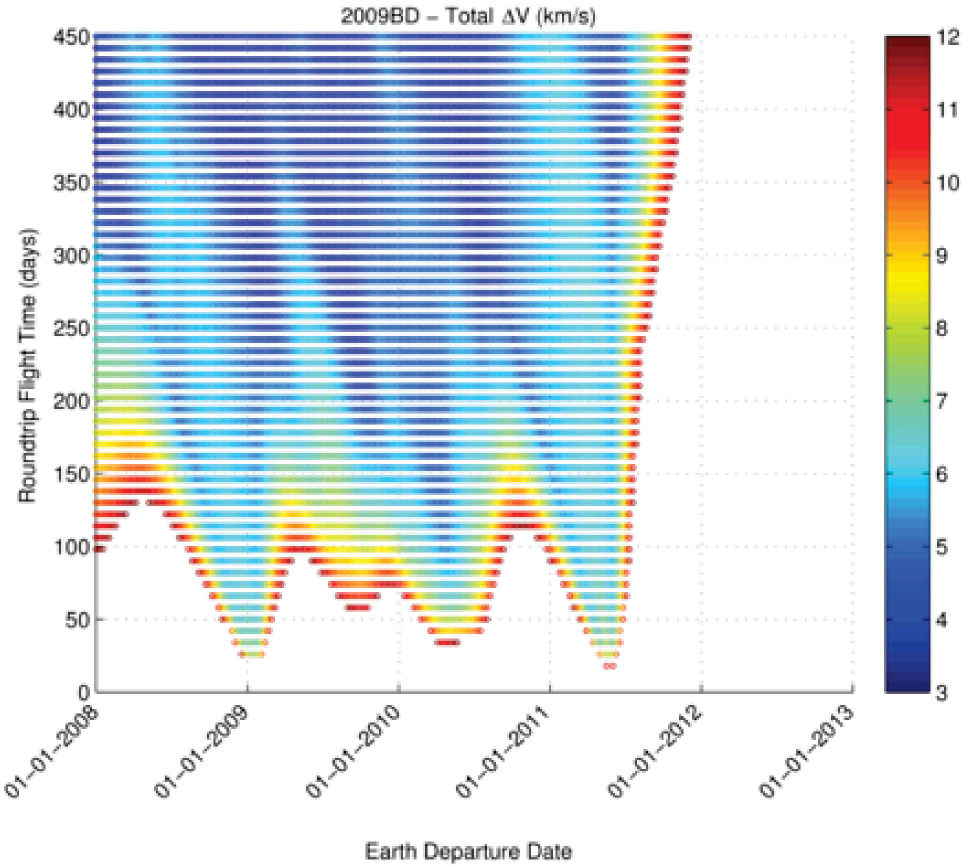


NHATS-like Analysis 2006–2007

PCC Comparison: 2009 BD



Standard NHATS Analysis 2015–2040



NHATS-like Analysis 2008–2012

Motion Relative to Earth: 2006 RH_{120}

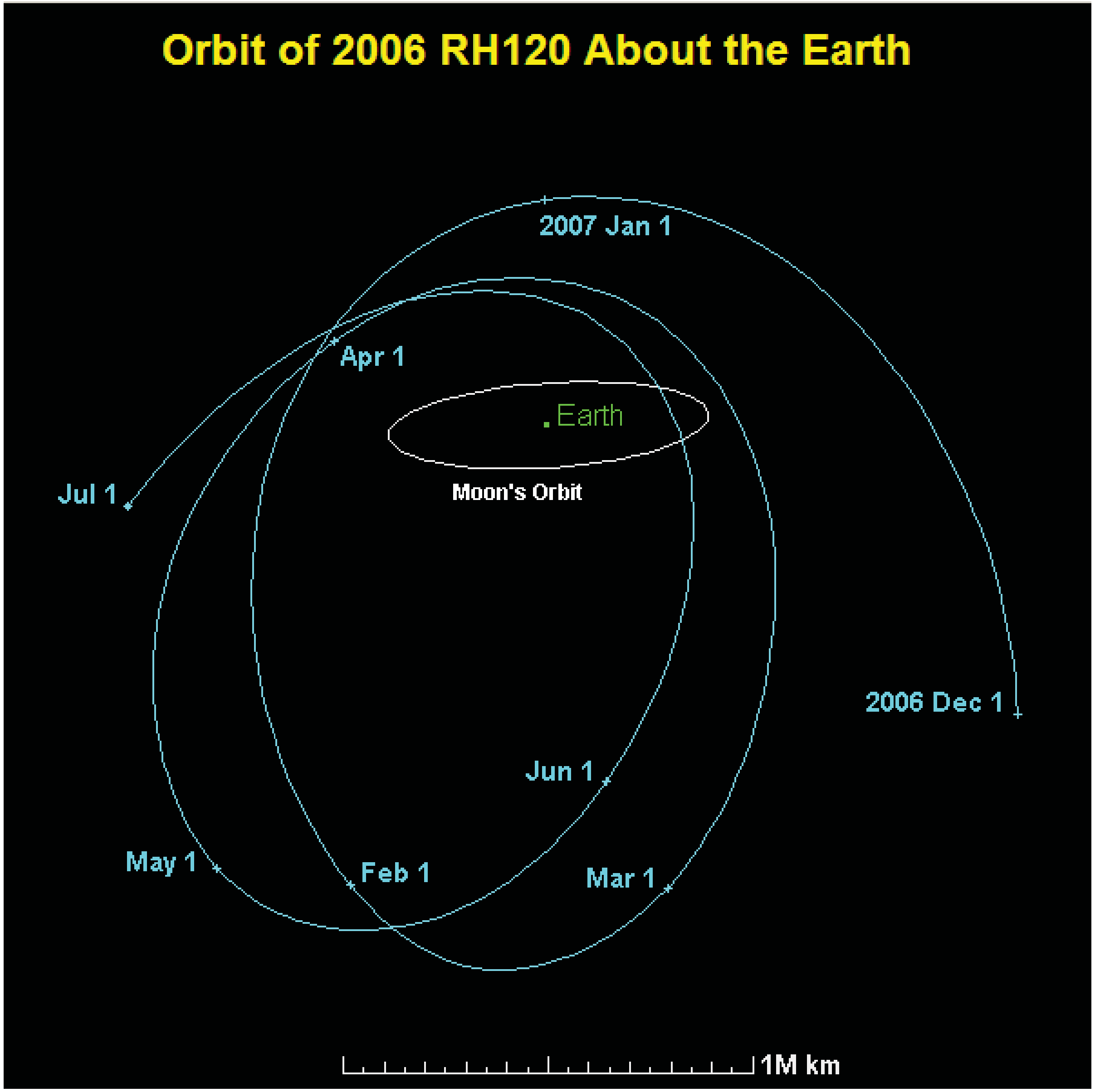
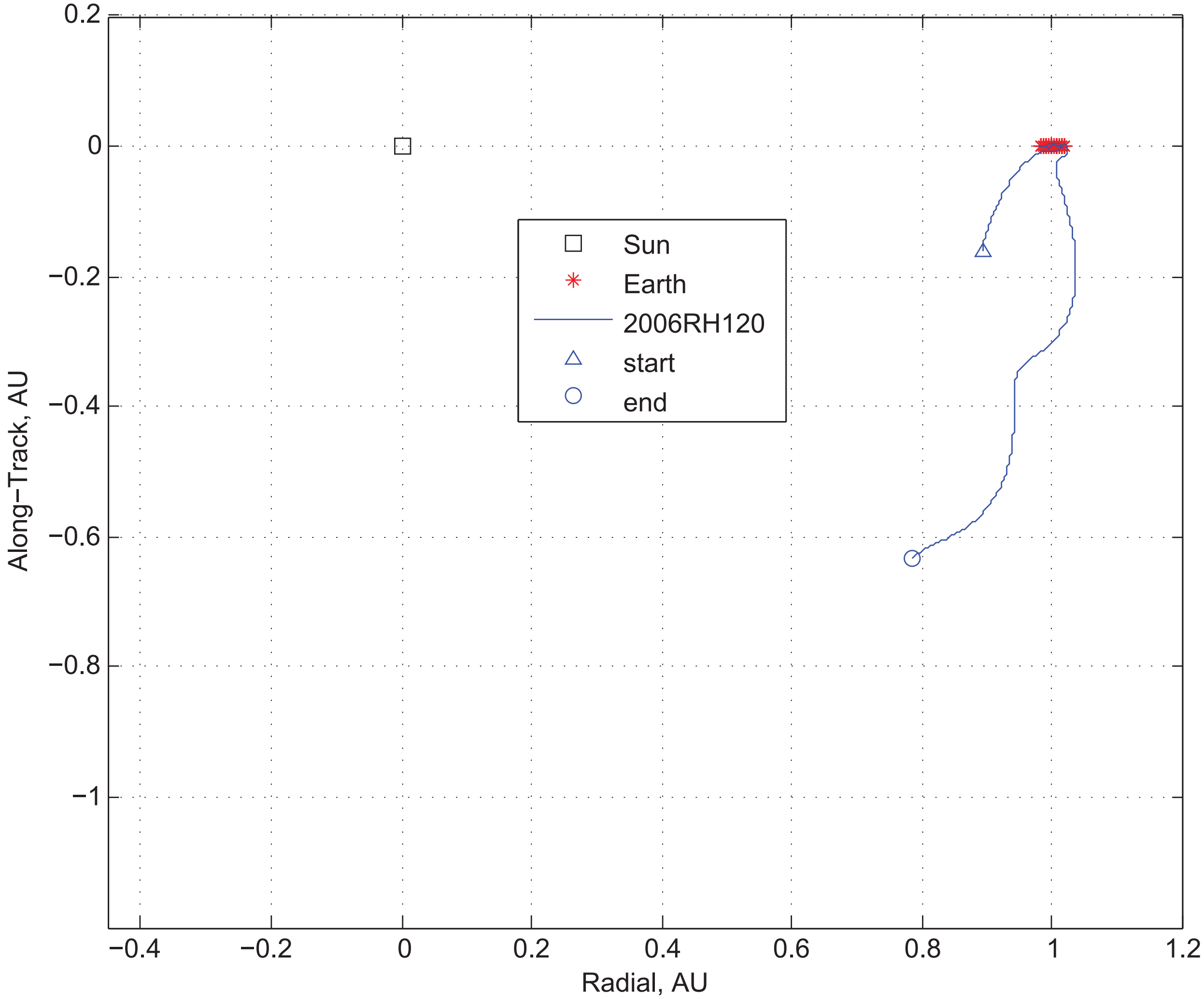


Image Credit: Paul Chodas/JPL

Motion Relative to Earth: 2006 RH_{120}



2006-01-01 to 2007-12-31

Motion Relative to Earth: 2009 BD

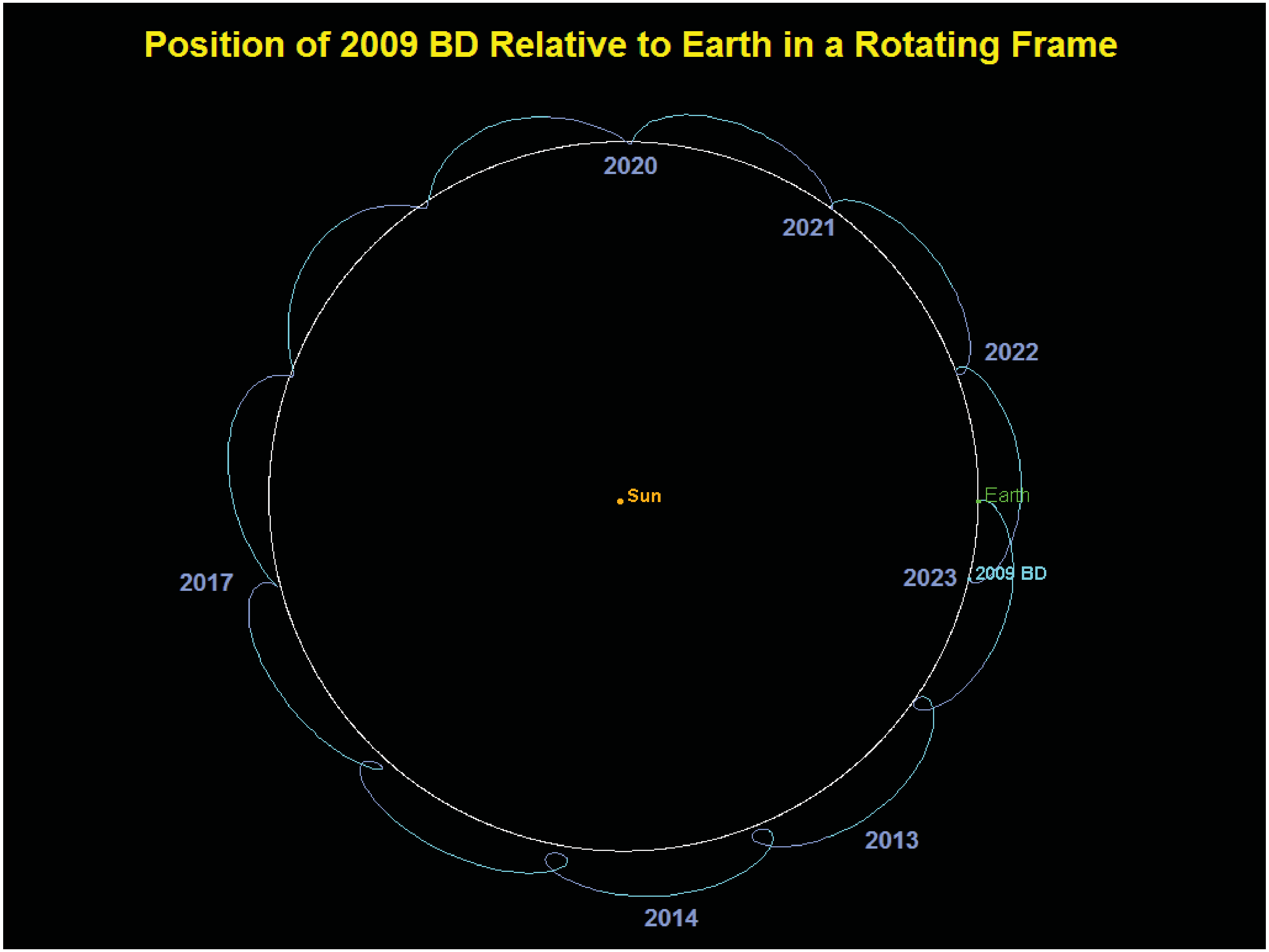
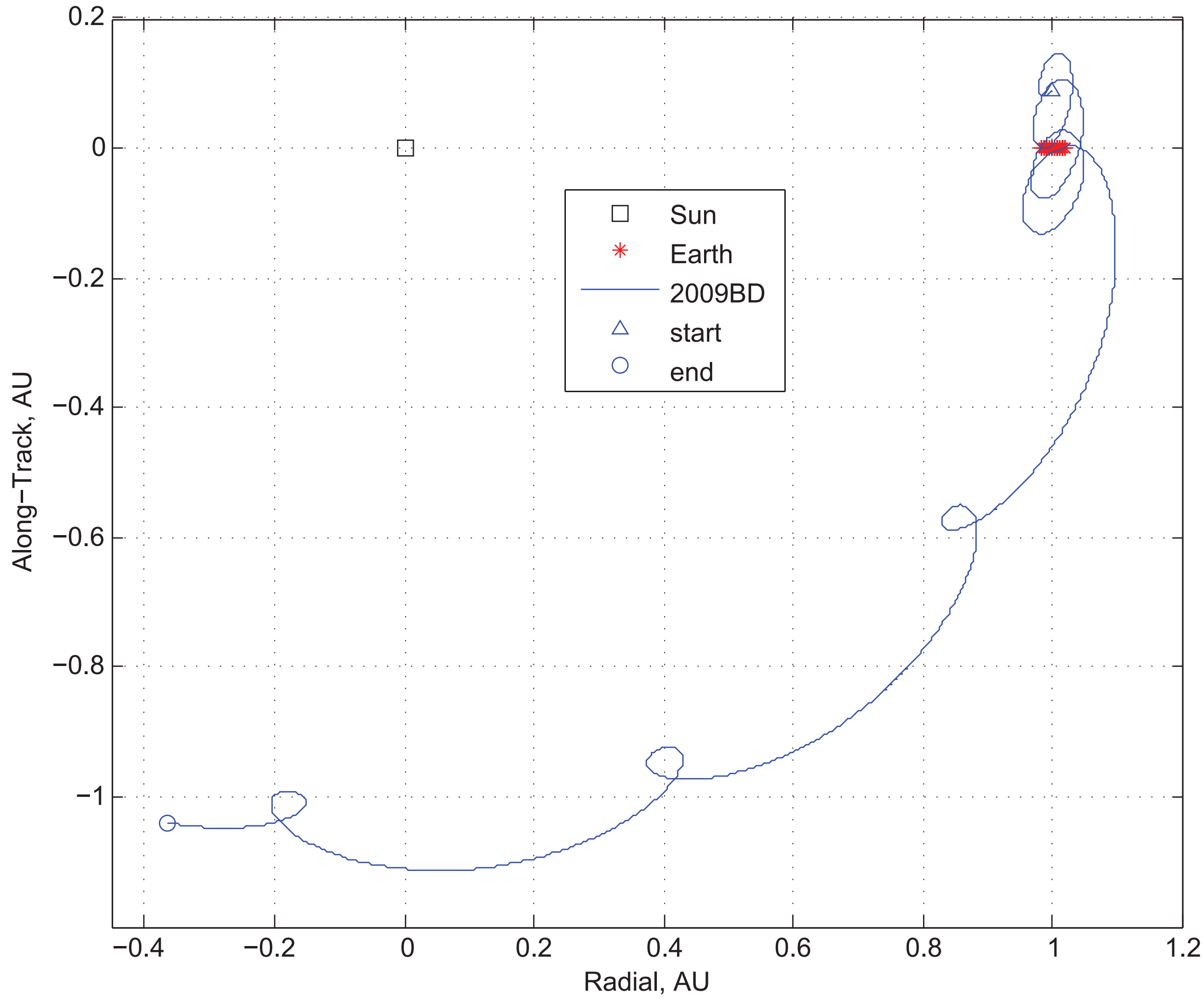


Image Credit: Paul Chodas/JPL

Motion Relative to Earth: 2009 BD



2008-01-01 to 2014-12-31